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A New Psychophysical Method for Determining the Photopic Spectral-luminosity Function of the Human Eye

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Using an 8 mm pupil, 2AFC-method, and 2×2 deg^2 grating at 2 c/deg we measured contrast sensitivity as a function of integrated radiance for a series of interference filters with peak wavelengths at 400–700 nm. Irrespective of the radiance level, contrast sensitivity was highest when wavelength was at and around 550 nm. It decreased towards longer and shorter wavelengths, reflecting the variation of the probability of quantal catch with light wavelength. When contrast sensitivity functions plotted in double logarithmic coordinates were shifted horizontally by multiplying the integrated radiances of each filter by an appropriate scaling factor, the functions superimposed onto a single curve. Contrast sensitivity at lower levels of relative radiance (*R*) increased in proportion to $\sqrt{R}$, obeying DeVries–Rose law, but at higher levels contrast sensitivity was constant, obeying Weber's law. Scaling factors plotted as a function of wavelength provided an estimate of $V(\lambda)$ quite similar to the standard 2 deg photopic spectral-luminosity function of CIE 1924. Copyright © 1996 Elsevier Science Ltd.

Human vision Photopic luminosity function Contrast sensitivity Quantal noise Light level

INTRODUCTION

In 1924 CIE introduced luminance as a photometric analog of radiance (CIE Proceedings, 1926). Luminance is proportional to the integrated radiance of a light source weighted by the standard photopic spectral-luminosity function $V(\lambda)$. The proportionality constant relates lumens to watts, and $V(\lambda)$ is normalized to unity at 550 nm. $V(\lambda)$ indicates the relative visual effectiveness of light of different wavelengths for a field of 2 deg in diameter. Thus, $V(\lambda)$ also indicates the relative number of light quanta absorbed by cone photoreceptors at various wavelengths. CIE 1924 $V(\lambda)$ is primarily based on measurements using heterochromatic flicker photometry and to some degree step-by-step brightness matching. The spectral-luminosity function has also been estimated using various other methods including visual acuity, motion minimization, brightness matching, minimal distinct border, absolute threshold, increment threshold, radiance for flicker fusion and reaction time. For a recent review, see Lennie *et al.* (1993).

In this study we introduced a novel method for the determination of the photopic spectral-luminosity function. It is based on the contrast detection model of human vision (Rovamo *et al.*, 1994). According to the model contrast sensitivity at each spatial frequency first increases in proportion to $\sqrt{I}$ obeying, DeVries–Rose law, when retinal illuminance (*I*) is smaller than critical illuminance, i.e. quantal noise is the dominant source of noise in the visual system. Thereafter the increase saturates and contrast sensitivity becomes constant and independent of retinal illuminance, obeying Weber's law, because internal neural noise has now become dominant. The external spectral density of quantal noise (Pelli, 1990) is the inverse of the external radiant flux (photons deg^{-2} sec^{-1}) entering the pupil of the eye while the internal spectral density refers to the inverse of the flux absorbed by photoreceptors.

Univariance principle implies that all quanta absorbed by photoreceptors produce identical responses. On this basis it is reasonable to assume that the internal spectral density of quantal noise corresponding to the transition between the square-root (Rose, 1942; DeVries, 1943) and Weber's laws is constant across the visible spectrum of light. With this accepted the transition point expressed in terms of external spectral density or its inverse, i.e. external radiant flux (photons/deg^2 sec), varies with the wavelength of visible light, because the probability of

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quantal catch in photoreceptors varies with wavelength.

In this study we measured monocular r.m.s. contrast sensitivity as a function of integrated radiance for a series of interference filters with peak wavelengths at 400–700 nm. The contrast sensitivity functions plotted in double logarithmic coordinates were thereafter shifted horizontally by multiplying the integrated radiances of each interference filter with an appropriate scaling factor in order to superimpose the functions onto a single curve. The scaling factors were then plotted as a function of wavelength to provide an estimate for the 2 deg photopic spectral-luminosity function $V(\lambda)$.

METHODS

Apparatus

The apparatus has been described in detail in Rovamo *et al.* (1994). Therefore, only its main features are described here. Cosine gratings were generated under computer control on a high resolution monitor driven in white mode at the frame rate of 60 Hz. The pixel size was $0.42 \times 0.42\ \text{mm}^2$ on the screen. The average photopic luminance of the display was measured with a Minolta Luminance meter LS-110. It was set to $50\ \text{cd/m}^2$, corresponding to a scotopic luminance of $130\ \text{cd/m}^2$, measured with a Bentham PMC 3B spectroradiometer. The CIE 1931 (x, y) chromaticity coordinates, measured with the spectroradiometer, were (0.30, 0.31).

The non-linear luminance response of the display was linearized by gamma correction. The Michelson contrast of simple cosine gratings was independent of spatial frequency up to 2 c/cm on the screen. A monochrome signal of 1024 luminance levels (10 bits) available from a palette of 65,536 luminance levels (16 bits) was obtained by using a video summation device (Pelli & Zhang, 1991), producing 8 bits within a range of 14 bits, and periodic dither signal (Näsänen *et al.*, 1993) producing two additional bits. The dither within the stimuli was completely invisible, because its Michelson contrast was about 0.007 when the contrast of the grating was equal to one and decreased to 0.0001 at the lowest grating contrast.

The number of different luminance levels was 1024 at or above Michelson contrast 0.027. At lower Michelson contrasts their number decreased reaching about 40 at 0.001, which was the lowest Michelson contrast available. Michelson contrasts of simple cosine gratings were checked with the Minolta Luminance Meter and found to be correct at and above 0.001.

Calibration of neutral density and interference filters

Integrated radiance transmitted through interference filters (Andover Corporation, Salem, NH 03079, U.S.A.) in $\text{mW/sr}\cdot\text{m}^2$ was measured by using a Bentham PMC 3B spectroradiometer. The peak wavelengths of the interference filters ranged from 400 to 700 at steps of 50 nm and their bandwidths at half height were 40 nm. During the measurements each filter in turn was placed in front of our CRT screen covered by black cardboard so that light only came out through the filter. The integrated radiances transmitted through the filters were 4.22, 18.8, 12.2, 12.4, 8.51, 1.30 and 5.95 $\text{mW/sr}\cdot\text{m}^2$ (i.e. $10^{-3}\ \text{J/sr}\cdot\text{m}^2\text{sec}$) at 400, 450, 500, 550, 600, 650 and 700 nm, respectively. The number of $\text{photons/sr}\cdot\text{m}^2\text{sec}$ transmitted through the filter was estimated by dividing the integrated radiance by the energy of a single quantum at the peak wavelength of the transmittance spectrum of the filter. The method of estimation is quite accurate, because the energy of a single quantum within the 40 nm bandwidth of a filter varies at most by $\pm 5\%$. The quantal energy was calculated as the product Planck's constant (6.62×10^{-34} Jsec) and the velocity of light (3.00×10^{17} nm/sec) divided by the peak wavelength. Thus, the estimated number of photons transmitted through the filters were: 0.850, 4.26, 3.07, 3.43, 2.57, 0.425, 2.10×10^{16} photons/$\text{sr}\cdot\text{m}^2\text{sec}$ at peak wavelengths 400, 450, 500, 550, 600, 650 and 700 nm, respectively.

The transmittance of neutral density filters (Lee Filters Ltd, Hampshire, U.K.) of 0.6 log units (No. 210 ND) at each peak wavelength was calibrated using the Minolta luminance meter. The luminance of a white light source was first measured through an interference filter placed tightly in front of the luminance meter and the other measurement was then completed with both the interference and neutral density filters placed in front of the meter. The ratio of these measurements gave the factor by which the filter reduced the number of photons at each wavelength. In logarithmic units the ratios were: 0.59, 0.65, 0.64, 0.55, 0.61, 0.59, 0.60 at 400, 450, 500, 550, 600, 650 and 700 nm, respectively.

Stimuli

Our stimulus was a simple vertical cosine grating within a square-shaped (2 cm × 2 cm) grating field. Spatial frequency was 2 c/cm. Its equiluminous surround was limited to a circular field (diameter 20 cm) by a black cardboard. The surround always had the same chromaticity as the grating.

The grating stimuli were created and experiments were run using software developed by one of the authors (RN). For further details see Rovamo *et al.* (1993). Grating contrast was changed in steps of 0.1 $\log_{10}$ units. The stimuli were quickly switched on and off by changing the colour look-up table during the vertical retrace period of the display.

Procedure

The experiments were performed in a dark room, where the only light source was the computer screen. The subject's head was stabilized using a chin rest. Fixation was monocular and directed to the centre of the stimulus field. No fixation marks were used.

The pupil of the dominant eye was dilated to 8 mm with two drops of 10% metaoxedrine hydrochloride, which leaves accommodation unaffected. Without any filter in front of the eye the average retinal illuminance produced by our display was thus 2500 phot td, corresponding to 6500 scot td. Each of the interference filters

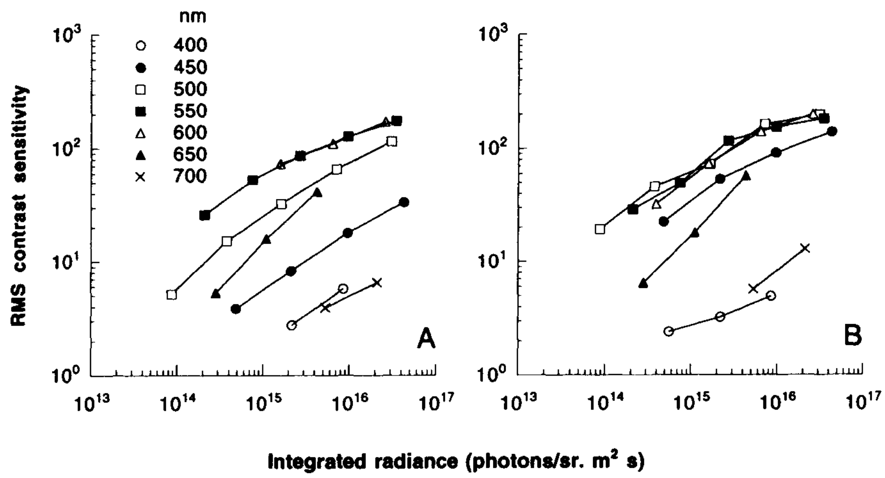

FIGURE 1. Monocular r.m.s. contrast sensitivity as a function of integrated radiance for vertical cosine gratings at various wavelengths of visible light. Viewing distance was 57.3 cm. Grating area was 2×2 deg^2 and spatial frequency 2 c/deg. Fixation was directed to the centre of the stimulus field. In (A) subject TK used the left eye and in (B) subject HR used the right eye.

was in turn placed in front of the dominant eye by using a special trial frame. The other eye was covered by a black eye pad. Lower levels of illuminance were obtained by placing a desired number of neutral density filters on the screen. After each luminance reduction of 0.6 log units due to the addition of another neutral density filter, the subject adapted to the new screen luminance for 5 min with interference filter in front of the eye. For further details see Rovamo *et al.* (1994).

Contrast sensitivity is the inverse of r.m.s. contrast at threshold. The thresholds were determined by means of a two-alternative forced-choice algorithm with four-correct-then-down/one-wrong-then-up rule. For further details see Mustonen *et al.* (1993). Each trial consisted of two 500 msec exposures accompanied by a sound signal. The observer indicated which exposure contained the grating by pressing one of the two keys on a computer keyboard. A wrong choice was followed by another sound signal to provide feedback about an incorrect response.

The threshold contrast required for the probability of 0.84 correct was estimated as the arithmetic mean of the last eight reversal contrast (Wetherill & Lewitt, 1965). All the data points shown refer to the medians of at least three threshold estimates.

Subjects

Two experienced subjects, aged 22 and 26 yr, served as observers. TK was a corrected astigmatic myope (od. −6.0 DS/−0.75 × 15/os. −7.25 DS/−0.75 × 165) and HR was a corrected hyperope (oa. +0.75 DS). Their accommodation had a range of 6 D. Hence, they were optimally corrected at the viewing distance of 57.3 cm used in our experiments. With optimal refraction their binocular Snellen acuities at 6 m were 1.2 (TK) and 1.5 (HR).

R.m.s. contrast

The contrast energy of the grating was calculated by numerically integrating the square of the contrast waveform $c(x,y)$ of the grating signal:

$$E = \sum \sum c^2(x,y)p^2, \quad (1)$$

where $c(x,y) = [L(x,y) - L_O]/L_O$ is local contrast, $L(x,y)$ the luminance distribution across the grating, L_O the average luminance across the screen, and p^2 the area of each image pixel in solid degrees. R.m.s. contrast was then calculated as

$$c_{\mathrm{r.m.s.}} = \sqrt{(E/A)}, \quad (2)$$

where A is stimulus area. For simple cosine gratings, r.m.s. contrast is equal to Michelson contrast divided by $\sqrt{2}$.

RESULTS

In the experiments of Fig. 1 we measured monocular r.m.s. contrast sensitivity as a function of integrated radiance (photons/sr·m^{2}sec) for vertical cosine gratings at the spatial frequency of 2 c/deg. Test grating area was 4 deg^2. Within the radiance range tested retinal illuminance was at least 0.1 phot td in Fig. 1. Irrespective of wavelength the grating field retained its original colour (hue and saturation) at all radiance levels. This suggests that the contribution of rods to contrast sensitivity was minimal even at the lowest radiance levels.

The integrated radiance (a radiometric measure analogous to luminance) transmitted through an interference filter is directly proportional to the external radiant flux (photons/deg^{2}sec) (a radiometric analogue of retinal illuminance), because the pupil was dilated and thus had the same area irrespective of light intensity. For further details see Wyszecki and Stiles (1967).

As Fig. 1 shows, contrast sensitivity measured through all interference filters used in the experiments increased with integrated radiance, expressed in terms of photons/sr·m^{2}sec. Contrast sensitivities were highest when light wavelength was at and around 550 nm. At shorter and

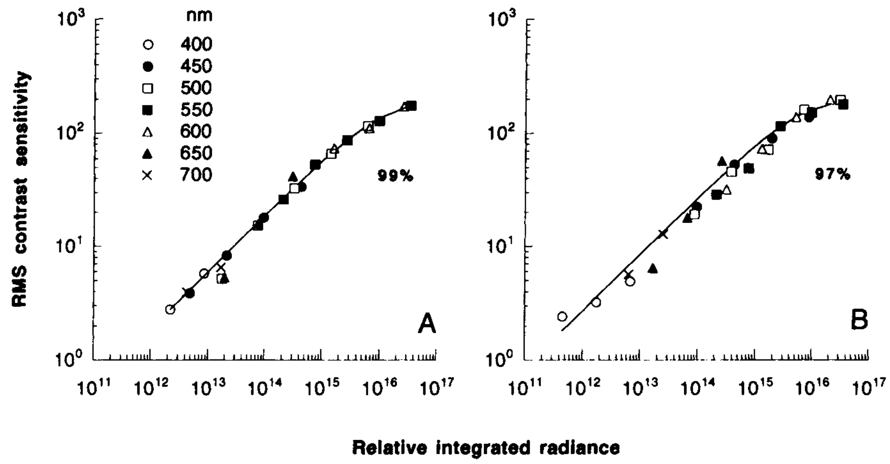

FIGURE 2. Contrast sensitivity functions of Fig. 1 were shifted horizontally to the left by multiplying the integrated radiances at each peak wavelength by an appropriate scaling factor in order to superimpose the functions onto a single curve. Smooth curves have been calculated by equation (3) fitted to the data of each frame separately. Explained percentage of the total variance indicates the goodness of the fit.

longer wavelengths contrast sensitivity decreased considerably. This reflects the fact that human eye is more sensitive to light at and around 550 nm than at shorter or longer wavelengths.

For Fig. 2, we shifted the contrast sensitivity functions horizontally in order to compensate for the variation of the probability of quantal catch in photoreceptors as a function of wavelength. This was obtained by multiplying the integrated radiances of each peak wavelength by an appropriate scaling factor in order to superimpose the contrast sensitivity functions onto a single curve. The contrast sensitivity functions measured at 550 and 600 nm in Fig. 1(A) and at 500 and 550 nm in Fig. 1(B) were already superimposed. Hence, they remained at their original location with respect to the horizontal axis and consequently their scaling factors were all equal to unity.

As Fig. 2 shows scaling operation was quite successful. The increase of contrast sensitivity with relative integrated radiance obeyed the DeVries–Rose square-root law at lower radiances and showed a clear sign of transition towards Weber's law (constant contrast sensitivity) at higher radiances. The two smooth curves in Fig. 2 were calculated by equation (3)

$$S = S_{\max}[1 + I_c/I]^{-0.5} \qquad (3)$$

fitted separately to the data of each frame in Fig. 2. For further details see Rovamo *et al.* (1994). The equation has been derived by combining the DeVries–Rose and Weber's laws (Mustonen *et al.*, 1993). In equation (3) S refers to r.m.s. contrast sensitivity, $S_{\max}$ to maximum

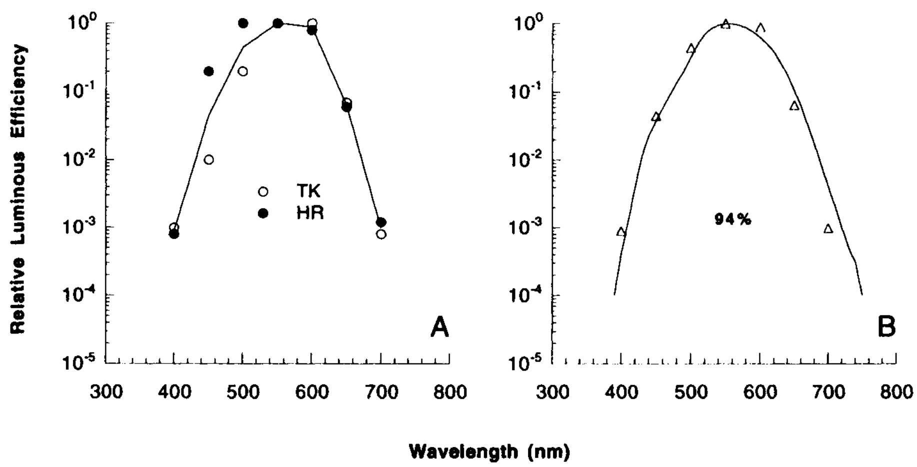

FIGURE 3. (A) Scaling factors of two subjects needed to superimpose curves in Fig. 2 were plotted as a function of light wavelength. Line segments connect the averages of the factors across wavelengths. (B) Averages of scaling factors (△) from (A) plotted as a function of light wavelength together with the continuous photopic spectral-luminosity function CIE 1924 $V(\lambda)$ for a field 2 deg in diameter. Explained percentage of the total variance indicates the goodness of the fit.

contrast sensitivity obtainable in bright light, I to retinal illuminance, and I_c to critical retinal illuminance marking the transition point between the DeVries–Rose and Weber's laws. Equation (3) is in complete agreement with our contrast detection model (Rovamo *et al.*, 1994) of human spatial vision. The goodness of the fit of each smooth curve to the data was estimated by calculating the percentage of the total variance explained (see Rovamo *et al.*, 1994). The percentages were found to be 97 and 99%.

In Fig. 3(A) we plotted the individual scaling factors needed to superimpose the contrast sensitivity curves as a function of wavelength. As Fig. 3(A) shows, the scaling factors of the two subjects were identical at 400 and 550–700. The intersubject difference of the scaling factors at 450–500 nm was 0.70–1.3 $\log_{10}$ units. In Fig. 3(B) the averages of the scaling factors were plotted as a function of wavelength. As Fig. 3(B) shows, the averages of scaling factors fell quite accurately on the CIE 1924 $V(\lambda)$ at all wavelengths. The CIE 1924 $V(\lambda)$ curve explained 94% of total variance in the averages of scaling factors.

DISCUSSION

Our experiments showed that contrast sensitivity increased as a function of integrated radiance for a series of interference filters with peak wavelengths at 400–700 nm. On the other hand, contrast sensitivity was highest when peak wavelength was at and around 550 nm and decreased towards longer and shorter wavelengths. When contrast sensitivity functions plotted in double logarithmic coordinates were shifted horizontally by multiplying the integrated radiances of each filter by an appropriate scaling factor, the functions superimposed onto a single curve. In agreement with our model of human spatial vision (Rovamo *et al.*, 1994) contrast sensitivity at lower levels of relative integrated radiance increased in proportion to the square-root of radiance, obeying DeVries–Rose law, but at higher levels of radiance contrast sensitivity was constant, obeying Weber's law. The model explained 97–99% of the total variance in the experimental contrast sensitivity data. When the scaling factors were plotted as a function of wavelength, the results of our two observers were quite similar except for 450–500 nm. Their mean was accurately (explained variance 94%) described by the standard 2 deg photopic spectral-luminosity function $V(\lambda)$ of CIE 1924.

As in earlier studies (Myers *et al.*, 1973; Kaiser & Ayama, 1986; Takahashi & Ejima, 1986) we used a criterion free 2AFC method to make our detection threshold data less subjective.

Our result that the scaling factors needed to equalize contrast sensitivity across wavelengths were independent of radiance level (photons/sr·m^2sec) but predictable from the photopic spectral-luminosity function $V(\lambda)$ is in agreement with the finding that for luminance-modulated gratings, foveal acuity (Pokorny *et al.*, 1968) and contrast sensitivity (Van Nes & Bouman, 1966; Kelly, 1973; Rovamo *et al.*, 1982; Ingling *et al.*, 1992) as well as peripheral contrast sensitivity (Rovamo, 1983) is independent of the spectral composition of the background provided that the average retinal illuminance is kept constant. However, the current study is novel in the sense that from the contrast sensitivities measured we derived an estimate that agrees with the standard photopic spectral-luminosity function $V(\lambda)$, while the previous studies cited above have only shown that acuity and contrast sensitivity are independent of wavelength or spectral composition on flicker-matched backgrounds.

The difference between the photopic spectral-luminosity functions of our two subjects at 450–500 nm agrees with the range of subject-dependent variation reported in the literature (Bedford & Wyszecki, 1958; Wagner & Boynton, 1972; Ikeda *et al.*, 1982). The difference between our subjects could at least partly be explained by the inter-individual variation of 0–1.0 $_{10}$log units in the optical density of macular pigment absorbing light effectively within 430–500 nm (Wyszecki & Stiles, 1967; Bone & Sparrock, 1971). On the other hand, the subject-dependent variation in crystalline lens absorption is not a likely explanation because the optical density of the lens increases with age (Wyszecki & Stiles, 1967) while the ages of our two subjects were about the same (22 and 26 yr). Furthermore, lens absorption is strongest at 400 nm (Wyszecki & Stiles, 1967; Coren & Girgus, 1972) where the results of our two observers were practically identical.

The mean of the estimates of the photopic spectral-luminosity function from our two observers was quite similar to the standard 2 deg photopic spectral-luminosity function $V(\lambda)$ of CIE 1924, whereas some other methods (see Lennie *et al.*, 1993), such as brightness matching (e.g. Wagner & Boynton, 1972; Comerford & Kaiser, 1975), increment threshold (King-Smith & Carden, 1976; Sperling & Hartwerth, 1971), and increment grating detection (Takahashi & Ejima, 1986), under certain experimental conditions give photopic luminosity functions broader than $V(\lambda)$. An obvious possibility for explaining the above deviations from $V(\lambda)$ is that the different techniques tap different underlying mechanisms, which have different spectral sensitivities (Lennie *et al.*, 1993). Thus, through the use of relatively high temporal and spatial frequencies (or brief and small stimuli) most methods provide good matches with $V(\lambda)$, as signals in chromatic pathways are attenuated. In addition, one possible reason (Lennie *et al.*, 1993) for the deviations from $V(\lambda)$ at high luminances is the profoundly non-linear effect of light adaptation.

When light intensity or flicker frequency in heterochromatic flicker photometry is increased, $V(\lambda)$ becomes narrower at long wavelengths (Bornstein & Marks, 1972; Marks & Bornstein, 1974; Pokorny *et al.*, 1993), possibly because of stronger wavelength-dependent adaptation (Pokorny *et al.*, 1993). However, in our experiments the shape of $V(\lambda)$ remained constant across the intensity range of 4.5 $_{10}$log units tested.

Chromatic adaptation tends to distort the photopic spectral-luminosity function especially when determined by using the method of heterochromatic flicker photometry (Eisner & MacLeod, 1981; Ikeda, 1983; Pokorny *et al.*, 1993; Swanson, 1993). White adaptation fields and long interstimulus intervals have been used to reduce the effect of chromatic adaptation (Burns *et al.*, 1982; Ikeda, 1983; Takahashi & Ejima, 1986). However, we kept an interference filter in front of the eye when a series of integrated radiance levels were tested. Hence, the visual system was in turn strongly adapted to each narrow-bandwidth saturated light within 400–700 nm. Despite this, our method provided a good estimate of the standard 2-deg photopic spectral-luminosity function $V(\lambda)$ of CIE 1924. This supports the view that $V(\lambda)$ is due to a postreceptoral mechanism (Lennie *et al.*, 1993).

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